An Automated Vacuum Extraction Control System for Soil Water Percolation Samplers

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ABSTRACT

A vacuum applied to soil water percolation samplers permits collection of both macro- and matrix-pore liquids. Performance of these field samplers is improved when the extraction vacuum is adjusted in accordance with the tension in the surrounding soil. This is particularly important when monitoring a network of spatially distributed samplers and for samplers installed in medium to fine textured soils. We designed a vacuum extraction system to more efficiently collect vadose-zone soil solution samples. A single vacuum pump, vacuum tank, and air dryer provided a vacuum supply for 12 soil water sampling sites via a branching polyethylene pipe network. A vacuum controller containing two inexpensive pressure transducers, a voltage regulator, relay, and solenoid valve was developed and tested for field installation. Data loggers operated the controllers, monitored extraction vacuum and ambient soil water potential, and adjusted relative vacuum at each percolation sampling site. The automated vacuum controllers successfully maintained sampler extraction pressures at levels proportional to ambient soil water potential and provided the added benefit of recording the pressure values for use in subsequent data interpretation.

If designed appropriately, tension samplers collect macropore and matrix-pore soil water from a known cross-sectional area and provide a means of measuring pore-water solute concentration and estimating downward water flux (Duke and Haise, 1973; Wilson et al., 1995). For a tension sampler to collect water moving downward in response to a soil-water tension gradient, the sampler's collecting surface is oriented horizontally and the applied tension is adjusted to match in situ soil conditions. If the in situ soil water tension is different from the suction applied to fixed-tension sampler, it can cause water-flow convergence or divergence near the intake membrane, which produces errors in measured water flux (Cochran et al., 1970; Haines et al., 1982).

This problem may be lessened if tension samplers are designed with side walls. The soil volume confined in samplers with sidewalls is thought to reduce the influence of varying soil water potential on water flow through the sampler opening (Corey et al., 1982). If tension sampler sidewalls extend upward through the soil profile too far, however, they may interfere with subsurface lateral flow processes in some soils and bias measured downward fluxes and leachate solute concentrations. Annual percolation fluxes measured with walled fixed-tension samplers differed from tile-drain-flow values by 0 to 33% (Montgomery et al., 1987). Hergert (1986) reported that average annual percolation fluxes measured from fixed-tension samplers differed from water-balance values by 3 to 72%.

Duke et al. (1970) developed a mercury manometer and electrode-based controller for a soil water sampler system. When coupled with a soil tensiometer, the device automatically adjusted vacuum levels supplied to the sampler tension plate in relation to in situ soil water potential. In field tests, the manometer system proved to be impractical owing to its excessive maintenance requirements, and a manual system was substituted (Duke and Haise, 1973). More recently, Brye et al. (1999) deployed a rectangular equilibrium-tension sampler with 2.5-cm-high sidewalls. The researchers manually adjusted sampler suction to match the soil water potential of the surrounding bulk soil, which they measured with two heat-dissipation sensors. Brye et al. (1999) concluded that, while an automated sampler-suction control would have been an added refinement, the manual suction adjustment procedure was adequate for their field conditions because soil water potentials at the 1.4-m sampler depth tended to vary slowly. Natural rainfall supplied their field water inputs.

We installed vacuum extraction soil water percolation samplers in a medium-textured soil at the 1.2-m depth to intercept and sample both macro- and matrix-pore liquids in *furrow-irrigated* soils. Furrow irrigations supplied from 2 to 5 cm of water in a single 12- to 24-h irrigation and were repeated on 10- to 14-d intervals during the growing season. These inputs produced greater and more rapid changes in soil water content than may occur under natural rainfall. We wished to automatically adjust sampler extraction vacuum to in situ soil water tension conditions at each sampling site.

Initially, a mercury manometer switch was used to control extraction vacuum, with furrow inflow-end samplers maintained at a lower extraction vacuum than outflow-end samplers. However, operating the manometer was inconvenient because pressure switch settings were difficult to adjust and lacked precision, water contaminated the mercury and compromised electrode function, and the power supply transformer failed. Like Duke and Haise (1973), we decided that the mercury manometer-base system required excessive maintenance and was unreliable.

Our objective was to design and field test an automated vacuum controller that was capable of tracking ambient soil water tension near the soil water sampler opening, and adjusting sampler vacuum to a user-specified target value. This new system needed to be more reliable and require less maintenance than the mercury manometer systems.

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Abbreviations: PVC, polyvinyl chloride; SDF, sampler drainage fraction.

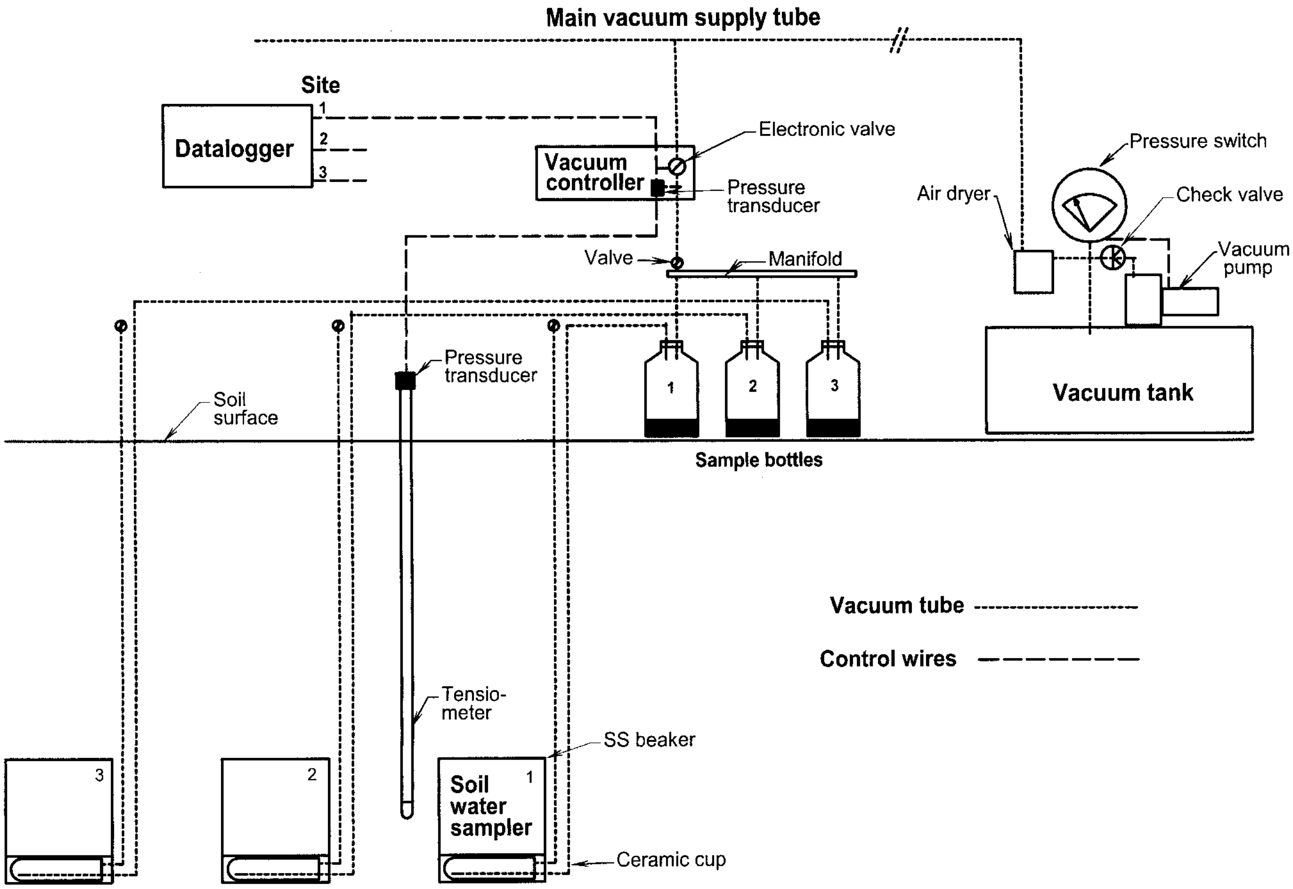

Fig. 1. Schematic diagram of a portion of the percolation monitoring system, including samplers, collection flasks, and the extraction vacuum controller installed at each of 12 sampling sites, and connections to the data logger and main vacuum supply.

MATERIALS AND METHODS

Field Setup

The study plot was a 50- by 180-m field located near Kimberly, ID. Three soil water percolation samplers ≈0.5 m apart and a tensiometer tube were installed at the 1.2-m depth at each of 12 sampling sites (Fig. 1) located in a 48- by 122-m area within the plot. Half of the sampling sites were located 30 m from the furrow inflow end and half near the outflow end. A single vacuum source was located outside the plot, 70 m from the inflow-end of the field. A 15-mm polyethylene pipe connected the vacuum source to each site. A pressure transducer was sealed to the top of the tensiometer tube with connections linking it to the vacuum controller. An insulated cover placed over the projecting tensiometer tube and transducer moderated temperature effects on tension measurements. The controller was housed in an aboveground, insulated sample box and regulated the pressure in three collection flasks (one per sampler), also housed in the box. One Campbell Scientific Inc. 21X programmable data logger (Logan, UT)[1] operated vacuum controllers and collected soil tensiometer, extraction pressure, soil temperature (thermocouples), and soil water content data (Campbell Scientific Inc. CS-615s) from three sampling sites. Table 1 lists the total number of components installed in the field plot for measuring and sampling soil water percolation.

Percolation Samplers: Design, Testing, and Installation

The sampler was constructed from a 23-cm-deep, 20-cm-diam. stainless-steel beaker. A 17-cm-long, 4-cm-diam. ceramic cup with 50 kPa air-entry characteristic was fitted with a Teflon plug containing two Teflon compression fitting, male pipe adapters [3.2 mm (1/8″) o.d. × 1.6 mm (1/16″) national

[1] Mention of trademarks, proprietary products, or vendors does not constitute a guarantee or warranty of the product by the USDA-ARS and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

Table 1. The total number of components installed in the field plot for measuring and sampling soil water percolation (excludes thermocouple and CS-615 sensors).

Field position	Data loggers	Sampler sites	Samplers	Vacuum collection flasks	Soil tensiometers 1.2 m	Automatic vacuum controllers	Controller components: Electric flow valves	Controller components: Pressure transducers
Inflow-end	2	6	18	18	6	6	6	12
Outflow-end	2	6	18	18	6	6	6	12
Total	4	12	36	36	12	12	12	24

pipe thread]. The bottom positioned pipe adaptor was drilled out, permitting a 3.2 mm o.d. Teflon collection tube to be inserted through it and terminate near the cup base. A second Teflon tube connected to the upper fitting. The ceramic cup assembly was placed in the bottom of the beaker and Teflon tubes passed through holes drilled near the beaker base. A water/silica-flour (200 mesh screen) slurry was poured into the beaker, encasing the ceramic cup in a 5-cm-deep layer. The silica layer's flat upper surface provided good soil contact. The depth of soil filling in the samplers (18 cm) was designed to obtain a valid percolation-water sample from the field soil across a range of applied suction (Corey et al., 1982) and ensure that large macropore flows were entirely captured.

A laboratory study determined how differences between sampler extraction tension and in situ soil tension influenced sampled percolate volume. We installed a percolation sampler of the above design in a 0.58-m-diam., 0.81-m-deep plastic barrel (Fig. 2). Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcids) subsoil was sieved through a 5-mm screen and slurried into the barrel in four portions. Five 2.54-cm-diam., 67-cm-long glass fiber wicks allowed drainage to occur under tension. Irrigation water was applied to the soil surface at a constant rate of 0.25 mm h^{-1}, a given extraction tension was applied to the percolation sampler for a period of 1 to 6 h, and sampler-drainage-rate and total-drainage-rate were measured using electronic scales. Sampler extraction tension was expressed as a fraction of the in situ soil tension and identified as the *extraction-soil-tension ratio*. The volume of percolate collected from the sampler per unit time was expressed as a fraction of the total drainage rate and termed the sampler drainage fraction (SDF). Assuming that downward water flux through the packed soil was uniform, the Expected SDF equaled (sampler cross-sectional area) $\times$ (total drainage cross-sectional area)$^{-1}$. The experiment was run twice. We removed and inspected the sampler and reinstalled it in the barrel prior to the second run. Results of the second run were similar to those of the first.

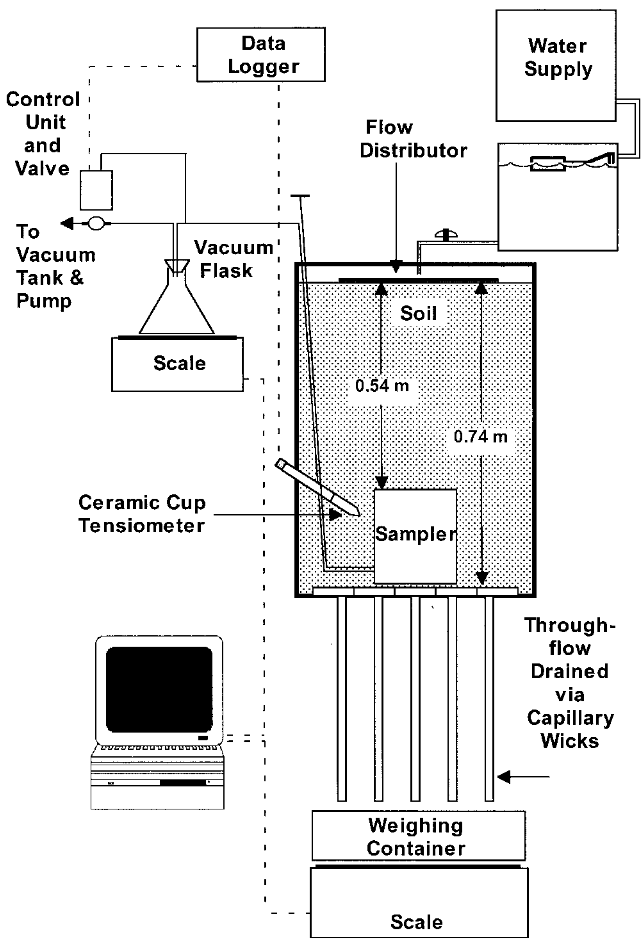

Fig. 2. Laboratory setup for testing percolation samplers, and determining the effect sampler extraction tension and in situ soil tension on percolation volume.

In the field, we installed percolation samplers, CS-615s, and thermocouple sensors by inserting the devices horizontally through the sidewall of an access pit (Fig. 3). A backhoe trench was dug 0.2 m away from, and parallel to, the monitored irrigation furrow. Three horizontal cavities were excavated into the pit sidewall. A specially designed tool was used to cut a circular slot 20 cm in diameter and 5 to 10 cm deep into the cavity ceiling. Soil was tamped into the samplers and a 2- to 3-cm layer of slurried soil placed on its surface to make good contact with the cavity-ceiling soil as the sampler was pushed upward into the carved slot. Thus the soil column extending from within the sampler upwards to the soil surface remained undisturbed. Cinder block and cedar wedges were used to firmly press and hold samplers against the soil mass. Sampler tops were set at the 1.2-m depth.

A polyvinyl chloride (PVC) pipe buried at the 30-cm depth conveyed the tubes and wires 3 m down furrow, and across the field (perpendicular to furrows) to one of five buried risers located along the inflow- and outflow-end field positions. Subsoil was replaced and saturated with water to settle. The soil was allowed to drain for at least 24 h before the topsoil (upper 20 cm) was replaced and water-settled if necessary. Risers were constructed of two 30-cm-long, 30-cm-diam. PVC pipes. One vertical pipe section was buried 30 cm below the soil surface at the riser location. The second 30-cm section was attached to the first via a sleeve. The top of the upper riser projected $\approx$7 cm above the soil surface. Prior to field operations, sensor leads and sampling tubes were coiled inside the lower riser, the upper riser section was removed, a cover placed over the lower riser, and the entire assembly buried. After tillage the lower riser was uncovered and the upper section replaced. We finished installing the sampling system in the fallowed plot in August and tested its operation under two irrigations applied in September.

Automated Vacuum Controller

Two pressure transducers and a simple electronic circuit were used to measure ambient soil and sampler extraction tension, and to open or close an electric valve connecting the sampler to the vacuum supply. The controller included a plastic enclosure, electric flow valve, and manifold mounted on a PVC sheet (Table 2). The enclosure contained a circuit board manufactured from our design by Idaho Instrument (Twin Falls, ID), and included terminal blocks for connections to the data logger, valve, and tensiometer transducer (Table 2). On the circuit board, a switching circuit (R1, Q1; Fig. 4, Table 2) and relay controlled the flow valve circuit (D1, K1), 5 V regulated power supply circuit (U1) energized the transducers, and the sampler transducer circuit (H1) measured pressure supplying the three percolation sampler flasks.

Seven electrical conductors connect the controller to the data logger: +12 V and −12 V ground ($\leq$1 A); +5 V (1.5 mA) digital output port control for the valve; and high and low differential analog inputs for the two transducers. Four lines connecting the controller to the remote soil tensiometer transducer provided excitation, ground, and signal voltage. Each controller cost approximately \$123. This comprised \$85 for parts and \$38 labor, including a one-time set-up charge for circuit board fabrication.

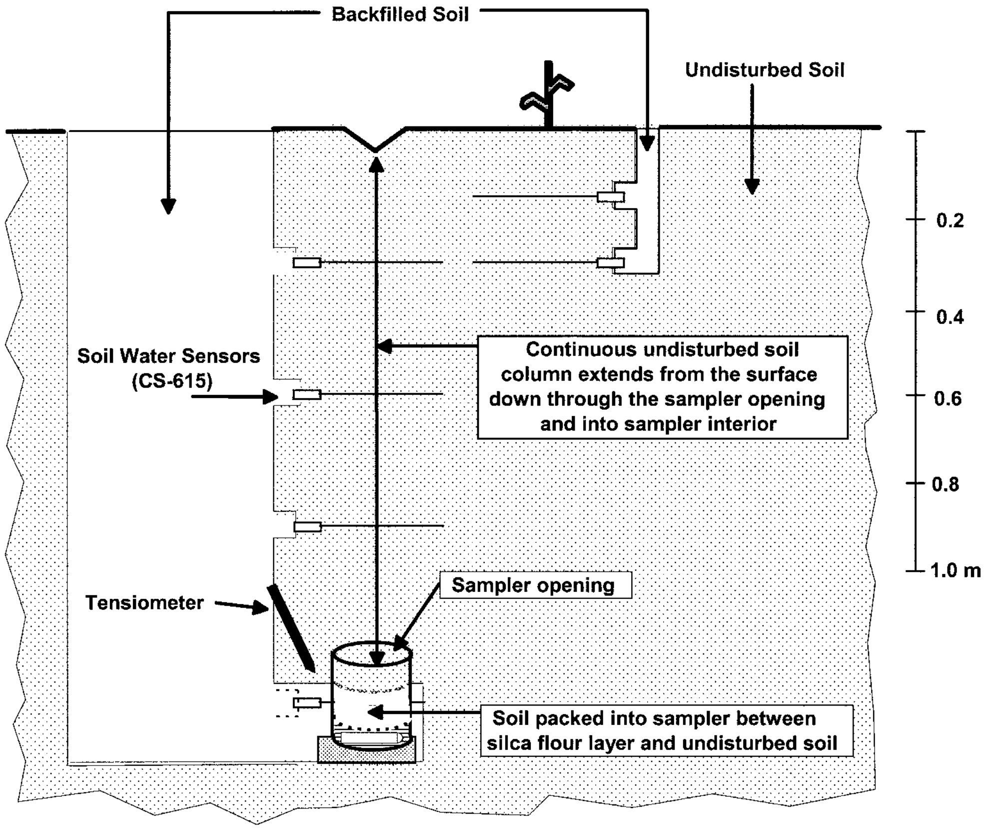

Fig. 3. Field installation and placement of soil water percolation samplers.

Controller Operation

The data logger checked system pressures at the samplers, which required a correction for sampler-transducer elevation differences, and made necessary adjustments at each sampling site every minute. For each of the three sampling sites monitored by the data logger, the program looped through a 40-cycle comparison procedure, which required 16 s to complete. At the start of each comparison cycle the soil tension and sampler system pressure were compared. If the sampler pressure exceeded that required for optimal percolation water measurement, the program reduced system pressure by opening the flow valve connecting the sampler system to the vacuum source. If the flow valve was opened in a previous cycle, and either the system pressure had attained the target value, or the 40-count loop was completed, the program closed the vacuum flow valve. The program did not exit the 40-count loop once target pressure was attained, but continued to check and adjust pressures to ensure that system pressures were stable.

The control system was not designed to correct sampler system vacuum if it exceeded the soil-tension-based target value. Soil water flows to the samplers and a slight leakage of air through tubing or valve connections were large enough that they caused sampler system pressures to decline across time. This loss of vacuum was significant enough that sampler vacuum levels rarely lagged behind target values during a declining soil-tension event, as when soil water contents near samplers increased after irrigation.

Table 2. Materials list for each automated vacuum extraction controller (manufacturer and part numbers in parentheses).

	Part	Quantity	Specification
	Plastic case	1	90 mm × 55 mm × 37 mm
	Mounting board	1	64 mm × 140 mm × 3 mm PVC† sheet
	Mounting bracket	1	22 mm length of 25 mm angle aluminum
	Electronic interface flow valve (Clippard Minimatic, Cincinnati, OH)	1	Normally closed, 2-way, 12 VDC‡, 0.67 w (ET-2M12-H[B])
	Flow valve manifold (Clippard Minimatic)	1	single supply w/1/8″ NPT§ inlet, 10-32 port outlet (15490-2)
	Differential pressure transducer (Omega, Stamford, CT)	2	0-1035 mb, Wet contact both sides diaphragm (PX26-015DV) Accuracy: 0.25 to 1% Full Scale (±3 to 10 mb)
H1	Soil tensiometer pressure		
H2	Vacuum flask pressure		
	3-position terminal blocks	3	Printed circuit board pin spacing
	4-position terminal blocks	1	Exterior case attached
K1	SPDT Relay (NTE Electronics, Bloomfield, NJ)	1	12-V, 5-amp (R46-503-12)
U1	5-V Regulator	1	(LM7805C)
Q1	Transistor (NTE Electronics)	1	2N2222A (NTE123AP)
D1	Diode	1	1N4148
R1	Resistors (all ±5%)	1	1500 Ω

† PVC = polyvinyl chloride.
‡ VDC = volts direct current.
§ NPT = national pipe thread.

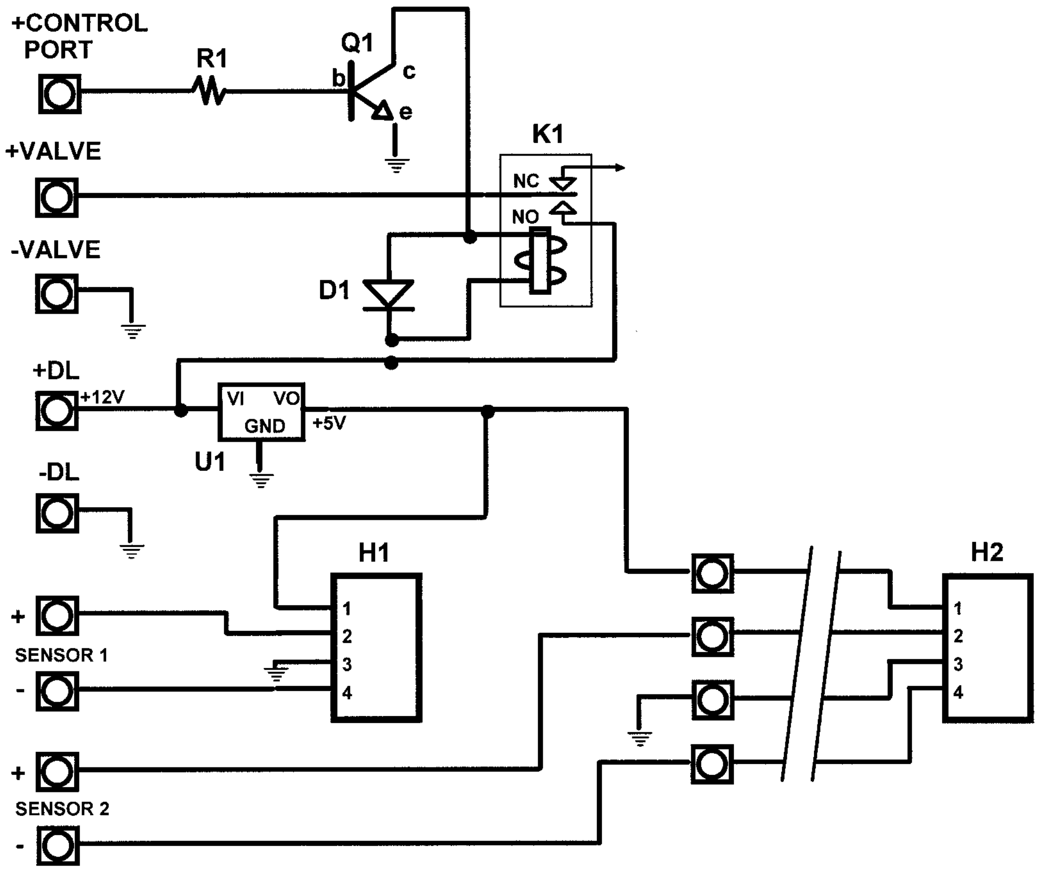

Fig. 4. Electrical circuit diagram for automated vacuum extraction controller. Components with identifier codes are further defined in Table 2.

If a soil tensiometer failed, causing the measured soil tension to fall below a user-defined value, the program would substitute either a mean soil tension value obtained from other vacuum controllers in the network, or a user-input soil tension value. This permitted the system to operate satisfactorily until the faulty tensiometer could be corrected.

RESULTS AND DISCUSSION

Soil tensions at 1.2-m soil depths varied spatially and temporally. We used a random subsample of soil tensions measured simultaneously on three separate days (0600 h; 6 July, 16 July, and 20 Aug. 1999) to assess spatial variability. The analysis compared (i) variation occurring across the field within a given field position, and (ii) overall variation, including that occurring between down-field positions (inflow-end vs. outflow-end). Data from the 3 d were analyzed together. Cross-field CVs averaged 13% with a 4.3 kPa standard deviation. Overall, soil water tension values ranged from 21 to 55 kPa at all locations with a mean of 37.7 kPa and CV of 28%. The mean soil tension at the inflow-end position was 29.7 kPa while that at the outflow-end was 46.2 kPa. Temporal variation in soil water tensions at the 1.2-m depth was greatest during the 1- to 3-d period following irrigations at inflow-end field positions. Soil water tension declined by as much as 9 kPa d^{-1} at such times, but decline rates varied with location.

The laboratory tests indicated that an extraction-soil-tension ratio of 1.44 $\pm$ 0.10 was optimal for our sampler in these soils. Theoretical, 2-dimensional calculations by Corey et al. (1982) showed that a long, trough-shaped sampler with a rectangular opening and 0.2-m sidewalls would operate efficiently in soils similar to ours at a sampler-soil extraction-ratio of 1.2. The cylindrical percolation sampler used here differed from that in the Corey et al. analysis. Extraction vacuum was applied to the soil in our sampler through a ceramic membrane and a layer of fine silica flour. Pore size, and hence conductivity of these intervening materials was less than that for the soil. This likely increased applied extraction tensions required to match flow through intervening materials to that of soil, especially at higher water contents.

When the sampler extraction-tension ratio differs from the optimum, drainage flow lines converge or diverge at the sampler opening, and cause an increase or decrease in the sampler's effective collection area. The relative change in the collection area for a sampler with a circular opening, per unit increase in radius, is greater than that produced by a similar increase in the dimensions of a rectangular sampler. Thus, errors related to the estimation of percolation flux can be minimized by maintaining correct extraction tension on the circular samplers. Maintaining proper extraction tension is even more critical when sampling at more shallow soil depths where water content and flux are more dynamic, and when sampling in fine-textured, well structured soils (Corey et al., 1982).

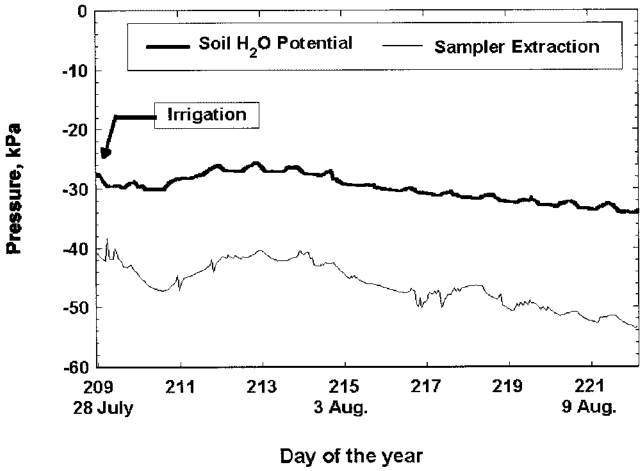

Fig. 5. Sampler extraction pressure and 1.2-m soil moisture tension from one sampling site, recorded over a 2-wk period beginning at furrow irrigation.

We installed automated vacuum controllers and soil tensiometers at each sampling site to reduce field labor requirements and increase sampling efficiency. This equipment adjusted sampler extraction pressure for individual sites, in response to soil tensiometer measurements taken at each site. This system was able to address both spatial and temporal variation.

The controller successfully regulated extraction vacuum in accordance with site soil water potential. Figure 5 illustrates the change in 1.2-m soil water potential and sampler extraction pressure that occurred across 13 d, starting on the day of a furrow irrigation (209, 28 July). The sampler extraction pressure paralleled the 1.2-m soil water potential closely. The sampler-soil extraction ratio ranged from 1.4 to 2.0 with a 13-d mean of 1.56. The sampler extraction pressure shown in Fig. 5 was measured after each adjustment cycle had been completed. The sampler system pressure increased slowly until the next adjustment event reestablished target pressure levels. Thus, just prior to the adjustment events, the sampler-soil extraction ratio values had decreased to values that ranged from 1.3 to 2 and averaged 1.41 during the 13-d period. The automated controllers functioned well for two irrigation seasons, although occasional problems did occur. When collecting water samples from flasks, tubing can become inadvertently kinked. This can reduce air flow and prevent equilibration between vacuum supply and sampler system when the valve is opened. Sampler system flow exceeded the valve flow capacity at two sample sites. To maintain system pressure at sufficiently low levels, we had to connect the samplers at these sites directly to the vacuum supply. Some controller/electronic valve systems were subject to heavier duty cycles than others. The valves on these controllers worked well for two months of intense usage. Eventually, however, the flow rate through these components decreased until the controllers were unable to supply enough vacuum to the three collection flasks. These valves had to be replaced, although it is possible that they could have been refurbished. Temperature-induced fluctuations in soil tension measurements were apparent in tensiometer responses. These could be avoided by using an advanced tensiometer design (Hubbell and Sisson, 1998).

In the preliminary test conducted in September, we applied an average of 70 mm water over the whole field. Note that water application uniformity for furrow irrigation is poor. Actual amounts applied at the inflow-end may be several times greater than is received at the outflow end. Sampler volumes collected during this period indicated that percolation losses averaged 139 mm at the inflow end and 8 mm at the outflow end. These results were judged reasonable in view of the large differences in water application, and hence soil water content and conductivity, between the two positions, as evidenced by differences in soil water tensions at the 1.2-m depth.

The percolation samplers performed satisfactorily in the 3 yr following installation (results to be published in a later paper). No trend of reduced percolation with time was apparent in water volumes collected across three irrigation seasons, suggesting that clogging of ceramic-cup pores with precipitating $CaCO_2$ was a minor concern for these calcareous soils. Two buried data logger conductors failed during the period and were replaced by surface-run cables. Rodents like to chew on the Teflon sampler tubes. Traps and chemical deterrents helped to exclude them from the risers and buried cable runs. Each year we committed ≈40 man-hours of labor to install and remove equipment from the plot. An additional 15 man-hours were used to connect the extensive network of thermocouple and CS-615 sensors. Two to four individuals would move equipment out of the tractors path during the single cultivation done on the plot each year (2 to 4 man-hours).

Overall, the automated vacuum controllers were more effective than the mercury manometer used early in the study. The automated system was able to respond to spatially variable soil water potential conditions in the study area. The controllers were more reliable, and the level of maintenance required by the 12 field units was no greater than that required for the mercury manometer system. The automated system maintained a minimum sampler extraction pressure of ≈−70 kPa. Lower values would have produced extraction pressures at the sampler that exceeded the air entry pressure for the intake membrane. The controllers could function at even lower extraction pressures, for example, in systems having membranes with −100 kPa air-entry pressures, assuming that the system air-extraction rates were similar to ours.

The use of data loggers to operate the controllers was not a detraction because they were required for logging soil water content and temperature. Besides operating the vacuum controllers, the data loggers also recorded ambient soil water potential and sampler system pressure at each site. This information improved our ability to correctly interpret the field data. This system also allows the option of changing the sampler-soil tension ratio depending on soil tension or other factors.

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